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NCEL DYNAMIC TESTING MACHINE

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U. S. NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

INTRODUCTION

With the developing construction technology involved with blast-type loadings, there has evolved a greater need to know more precisely how structural materials respond to such loadings. A continuing task at this laboratory is the determination of the dynamic properties of basic materials for which such data is lacking.

As early as January 1961, the Bureau of Yards and Docks approved funds to conduct dynamic tests on a specially fabricated high-strength reinforcing steel (Task Y-F008-10-401, Dynamic Properties of Structural Materials). This steel had been used in partially prestressed concrete beams (Task Y-F008-10-102A); however, no information was available about the dynamic response of this chrome-alloy steel, identifiable as a modified A-431. The specific information desired was to determine the magnitude of any increase of values for yield stress associated with increasing rates of strain compared to a conventional static value.

Coincident with the immediate need for knowledge of the dynamic properties of this steel, as well as the long-range requirement for dynamically testing other materials, was the need for a high-speed testing machine capable of applying dynamic loads on standard steel tensile specimens at constant strain rates to about 1.5 to 2 inches per inch per second. Accordingly, promising dynamic testing machines were used to evaluate the capabilities of the machines and to obtain immediate information on the dynamic properties of the A-431 steel. None of the machines evaluated or investigated proved wholly adequate for the purpose. Either they were too slow or did not have adequate control over the head velocity at the testing speeds of interest. Consequently, specifications were written and a contract was awarded for the development of a suitable machine. Details of the initial tests of this steel together with specifications for the NCEL dynamic testing machine are delineated in TN-427.*

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* U. S. Naval Civil Engineering Laboratory. Technical Note N-427: Dynamic tests on high-strength steel, by W. L. Cowell and J. R. Keeton. Port Hueneme, Calif., 10 Feb. 1962.

The purpose of this report is to describe the ·' racteristics and capabilities of the testing machine supplied under contract, to p t the results of tests with the machine on the A-431 steel, and to compare these results with the earlier results obtained for this steel by other high-speed testing machines as reported in TN-427.

NCEL DYNAMIC TESTING MACHINE

The NCEL dynamic testing machine together with its electronic console is pictured in Figure 1. Schematic diagrams of the machine are presented in Figures 2 and 3. All numbered valves are electrically operated solenoid valves; lettered valves are hand-operated valves.

General characteristics of the machine are a maximum static capacity of 50,000 pounds and head velocities up to 15 inches per second. The piston stroke is 4 inches. Using the booster, the head velocity can be increased to 30 inches per second and the static load capacity can be increased to 80,000 pounds. The piston stroke at the higher velocity is 0.75 inch; the head velocity will reduce to 15 inches per second for the remainder of the 4-inch stroke. With standard steel tensile specimens (0.2-square-inch area), strain rates of 1.5 inches per inch per second can be obtained.

The basic operation of the machine proceeds as follows:

1. An operating air pressure, supplied by an external compressor, is introduced into the air side of the main accumulator. The selected air pressure determines the maximum load that can be applied with the testing machine.

2. The hydraulic pump's electrical switch is closed. This action, in addition to starting the pump, also opens valve No. 4 and closes valve No. 3. The pump introduces hydraulic fluid into the main accumulator, forcing the floating piston to the top of the accumulator. The pump continues to operate until at a preselected hydraulic pressure, in excess of the air pressure, a pressure switch turns off the pump and also opens valves No. 1 and 3 and closes valve No. 4. In addition to charging the accumulator, the pump pressure also closes the fast-opening valve.

3. The opening of valve No. 1 allowed the pressure to equalize on both sides of the main piston. The lower side of the main piston has a larger surface area because the lower piston rod is slightly smaller in diameter (d_1) than the upper rod (d_2). The resulting upward force slowly raises the main piston to the top of the cylinder and holds it there in a cocked position until the machine is fired. This machine condition is illustrated in Figure 2.

4. To fire the machine, a switch is closed starting a time relay. The first action is the closing of valve No. 1, which isolates the top from the bottom of the cylinder. The second action is the opening of valve No. 4, which releases the pressure that held the fast-opening valve closed. The air pressure acting under the piston of the fast-opening valve then fires the piston upward, opening the valve and allowing the fluid in the bottom of the cylinder to flow out and return to the reservoir. The hydraulic pressure acting on top of the main piston is maintained by the main accumulator and forces the piston down when the fast-opening valve opens. Figure 3 illustrates the general position of the machine parts after a test. The bag-type accumulators at the top and bottom of the fast-opening valve serve as surge tanks for the comparatively large volume of fluid discharged during a test.

5. The head velocity of the machine is controlled by several hand-operated metering valves designated A, B, and C. The settings for these valves are established before each test and are not changed until a new head velocity is desired.

6. The machine can apply a specific load and hold this load for a time interval before releasing it. This feature of the machine has not been used or fully evaluated at the present time. The time interval to reach the specified load is a function of the specimen resistance and is controlled by the hand-operated valves. The time from the beginning of a test until the load is released can be varied from 10 milliseconds to 3 seconds.

7. Static testing can be performed by closing valve No. 1 and apply the load by opening hand valve D.

Since the machine operates in one direction only, tensile specimens are attached to the upper piston rod and then to an adjustable column projecting down from a crossbeam. Each specimen connection is transferred through a ball joint to maintain uniaxial loading. Compression tests are carried out in the lower part of the machine by placing the specimen under the lower piston rod. The bearing surface on which the specimen rests is adjustable to varying heights. The bearing head attached to the lower piston rod contains a spherical seat.

MACHINE CALIBRATION

As presently used in loading materials at various strain rates, the machine has been calibrated in the following manner:

1. A series of curves has been developed for selected operating air pressures, showing the head velocity corresponding to a particular valve setting. These curves are shown in Figure 4.

2. Depending on the specimen configuration, the type of material, and the method of attaching the specimen (pinned or threaded), a reasonable relationship can be established between head velocity and strain rate. This relationship is illustrated in Figure 5. To obtain machine settings for testing a specimen at a specific strain rate, the corresponding head velocity is determined from Figure 5; valve settings are then obtained from Figure 4. After one test has been conducted, small adjustments in settings can be made, if necessary, to more precisely obtain the desired strain rate.

RECORDING INSTRUMENTS

Test data is recorded on an oscillograph using System D, 3-kc amplifiers. Basic information obtained in a test is the machine head displacement, the strain in the reduced section of the specimen, and the load resistance of the specimen as a function of time.

MACHINE PERFORMANCE CHARACTERISTICS

Initial tests with the machine revealed considerable oscillation in the load trace at the higher head velocities when the stress in a specimen reached yield. This undesirable characteristic was not confined to materials exhibiting both upper and lower yield points, which by their very nature would induce vibrations. A series of tests with aluminum specimens (a material not having a definite yield point) produced the same type of oscillation, which began at or near the proportional limit. At this time the load cell (50,000-pound capacity) was located between the ball-and-socket joint and the upper crosshead of the machine (see Figure 1). The frequency of the oscillation was approximately 400 cps, and occasionally the load trace showed an oscillation with a magnitude of 2,200 pounds. For a standard tensile specimen (0.2-square-inch area) this was equivalent to 11,000 psi.

Several attempts to stiffen the machine resulted in little improvement. Gages placed on the enlarged portion of the test specimen between the radius and threads did not exhibit the vibration. A small tension link was fabricated, instrumented with strain gages, and calibrated in a static testing machine to serve as a load cell. Figure 6 shows a typical test unit in place. The tension link screwed directly into the ball-and-socket joint. Figure 7 illustrates the improvement in the load trace using the tension link.

Another problem presented by the machine was a slow accumulation of air in the hydraulic fluid. As noted earlier, the pump pressure switch is set at some pressure higher than the air pressure used in the accumulator and, in effect, this pressurizes the air entrapped in the fluid, forming an uncontrolled accumulator within the hydraulic system. This entrapped air caused a high strain rate at the very beginning of a test, followed by a gradually lowering strain rate as the fluid pressure reduced to the air pressure in the main accumulator. A small valve was installed at the bottom of the main accumulator to bleed the entrapped air out of the hydraulic system, and a pressure gage was installed to indicate the hydraulic pressure in the system. The air and hydraulic pressures can be equalized prior to firing the machine by opening valve D (Figure 2), permitting hydraulic fluid to return to the reservoir.

The maximum operating pressure when using only the main accumulator is 1,800 psi. To obtain very high head velocities, the booster is used at pressures up to 2,800 psi. The capacity of the booster is large enough to maintain the higher head velocities through fracture of a steel specimen. The increase in head velocity when using the booster can be seen by referring to Figure 4. The pressure loss in the piping from the main accumulator becomes quite high as the head velocity increases. At the maximum valve opening, the head velocity when using the booster is double that of the machine without the booster. When it is necessary to test at head velocities in excess of 8 inches per second, it is desirable to use the booster.

For tensile test specimens used in this series of tests, the maximum strain rate obtained was just over 2 inches per inch per second. Previous tests using flat aluminum specimens with pinned connections produced strain rates up to 4 inches per inch per second. The increase in strain rate was due primarily to the lower modulus of elasticity of aluminum and to pinned connections rather than threaded connections.

TEST SPECIMENS

The test specimens reported in this series were machined from the same reinforcing bars as those reported in TN-427. The specimen configuration is shown in Figure 8. The mill analysis of this steel showed the following composition in percent:

C	Mn	P	S	Si	Cr
0.59	0.92	0.019	0.023	0.33	0.92

Strain in the reduced section was measured with a 1/2-inch foil-type resistance strain gage. The remaining arms of the bridge were formed with similar gages cemented to small blocks of steel (see Figure 6). Load was measured with a tension link similar to that shown in Figure 6.

TEST RESULTS

Results of the dynamic tests are shown in Table I. The strain rate was calculated from the trace of the strain gage in the reduced section of the specimen. As indicated earlier, the load was calculated from the output of a load cell connected directly to the test specimen. A typical oscillogram is illustrated in Figure 9.

Since this material exhibits a marked yield point, there was little difficulty in locating and determining the yield load. The maximum load and the rupture load are equally evident on the oscillogram. Measurements for percent elongation and percent reduction in area were made after the specimen had broken. The values shown in Table I for strain in the plastic zone were determined from the strain gage by calculating the difference in strain between yield and the point where strain hardening set in. The slope of the strain gage trace changes at each of these points of interest.

DISCUSSION

Figure 10 is a plot of the upper yield stress as a function of strain rate. The yield stress is a logarithmic function of the strain rate up to 1 inch per inch per second. At this value there appears to be a sharp increase in yield point. Tests reported in TN-427 on this same steel indicate reasonable correlation with the present tests at strain rates of 0.04 and 0.4 inch per inch per second. Test results from TN-427 and the straight-line equation that seemed to fit the data at that time have been included in Figure 11 along with the plots of the original data from the present test series. No explanation has been found for the apparent discrepancy of tests at the intermediate strain rates; although it should be stressed that results presented in TN-427 were obtained with machines and instrumentation as a whole somewhat inferior to the present NCEL equipment. The maximum increase in upper yield stress is approximately 25 percent higher than the average static yield stress at strain rates around 2 inches per inch per second.

The tensile strength has been presented as a function of the machine head velocity in Figure 12. An increase in tensile strength seems evident up to a head velocity of 1 inch per second. From this point up to 10 inches per second the curve is approximately level. The three tests conducted at head velocities in excess of 20 inches per second indicate a higher tensile strength. The results show considerable scatter, and definite conclusions on the rate of increase in tensile strength cannot be made. A general increase in tensile strength with the speed of testing is evident but is not greater than 6 or 7 percent of the static tensile strength.

Table I. Dynamic Test Results for Chrome-Alloy Steel

Strain Rate (in./in./sec)	Upper Yield Stress (psi)	Lower Yield Stress (psi)	Tensile Strength (psi)	Rupture Stress (psi)	Elongation (%)	Reduction in area (%)	Strain in Plastic Zone (μ in./in.)	Head Velocity at Ultimate Load (in./sec)
0.000074	96,000	96,000	147,000	—	14.5	55.3	—	—
0.0026	100,000	98,500	150,000	103,000	15.0	55.9	2750	—
0.0070	99,500	99,000	—	105,000	15.5	55.7	1900	—
0.029	103,500	100,500	154,500	107,000	15.5	53.6	1850	0.28
0.040	105,000	100,000	155,500	105,500	15.1	54.6	5450	0.43
0.044	104,500	104,000	159,500	113,000	14.0	49.9	2250	0.41
0.049	104,000	102,000	156,000	108,500	15.0	53.4	1650	0.41
0.087	108,000	105,500	158,500	109,000	16.5	52.9	3450	0.78
0.10	107,500	105,500	158,000	109,000	15.0	49.1	3550	0.97
0.11	113,500	107,000	163,000	108,500	16.2	53.6	2800	1.2
0.20	111,000	107,000	159,500	112,500	14.2	51.7	3150	2.5
0.21	110,000	107,000	160,500	112,500	14.6	51.9	2900	2.3
0.22	110,500	106,500	160,500	108,500	15.8	54.5	4250	1.9
0.28	108,000	107,000	157,000	190,500	13.0	53.0	2800	3.1
0.45	110,500	107,000	158,000	107,500	15.2	55.0	4500	3.0
0.45	113,500	109,000	161,000	109,000	16.0	54.2	5150	3.3
0.45	111,500	107,500	159,000	112,000	15.5	51.7	—	3.0
0.46	112,000	110,000	164,500	117,000	14.8	49.6	3420	2.7
0.46	111,000	105,000	158,000	107,500	16.0	53.4	3750	2.5
0.46	112,500	108,500	159,500	116,500	14.0	51.0	—	3.0
0.76	114,000	110,500	159,000	112,500	13.2	53.6	4700	4.7
0.84	113,500	107,000	156,500	106,000	16.0	55.5	—	6.8
0.93	117,000	113,500	162,500	109,500	17.0	52.4	—	6.3
0.94	113,500	109,000	156,000	109,000	15.0	54.7	—	8.5
0.95	114,500	107,000	157,500	105,000	16.0	65.1	—	9.0
1.1	114,000	107,500	157,000	104,000	16.0	55.5	—	10.1
1.9	118,500	117,000	161,000	112,000	16.2	55.4	—	31.6
1.9	120,000	120,000	165,000	116,100	16.0	54.7	—	33.8
2.1	121,000	121,000	166,500	113,500	16.0	54.1	—	33.6
2.2	122,500	122,000	—	125,500	16.0	54.6	—	35.5
0.000007*	95,900	—	151,800	108,400	16.0	50.5	—	—

* Average static measurements for six specimens (TN-427)

As noted in the previous tests reported in TN-427, there was no change in percent elongation or reduction in area at the testing rates used in this series. Figure 13 illustrates the ductile nature of the breaks observed with this steel.

FINDINGS AND CONCLUSIONS

Dynamic Testing Machine

1. The testing machine is adequate for determining the dynamic properties of standard steel tensile specimens at constant strain rates up to 1.5 inches per inch per second.

2. Strain rates slightly over 2 inches per inch per second were obtained for the chrome-alloy steel tested in this study.

Chrome-Alloy Steel

1. The upper yield stress increases linearly with the logarithm of the strain rate up to 1 inch per inch per second; however, beyond this point the increase in upper yield stress is curvilinear at an increasing rate. The increase in upper yield stress is approximately 25 percent at a strain rate of 2 inches per inch per second.

2. A general increase in tensile strength is evident with increased head velocities, but only about 6 or 7 percent higher than the static value.

3. Ductility, as measured by percent elongation and percent reduction in area, is not influenced by the speed of testing used in this investigation.

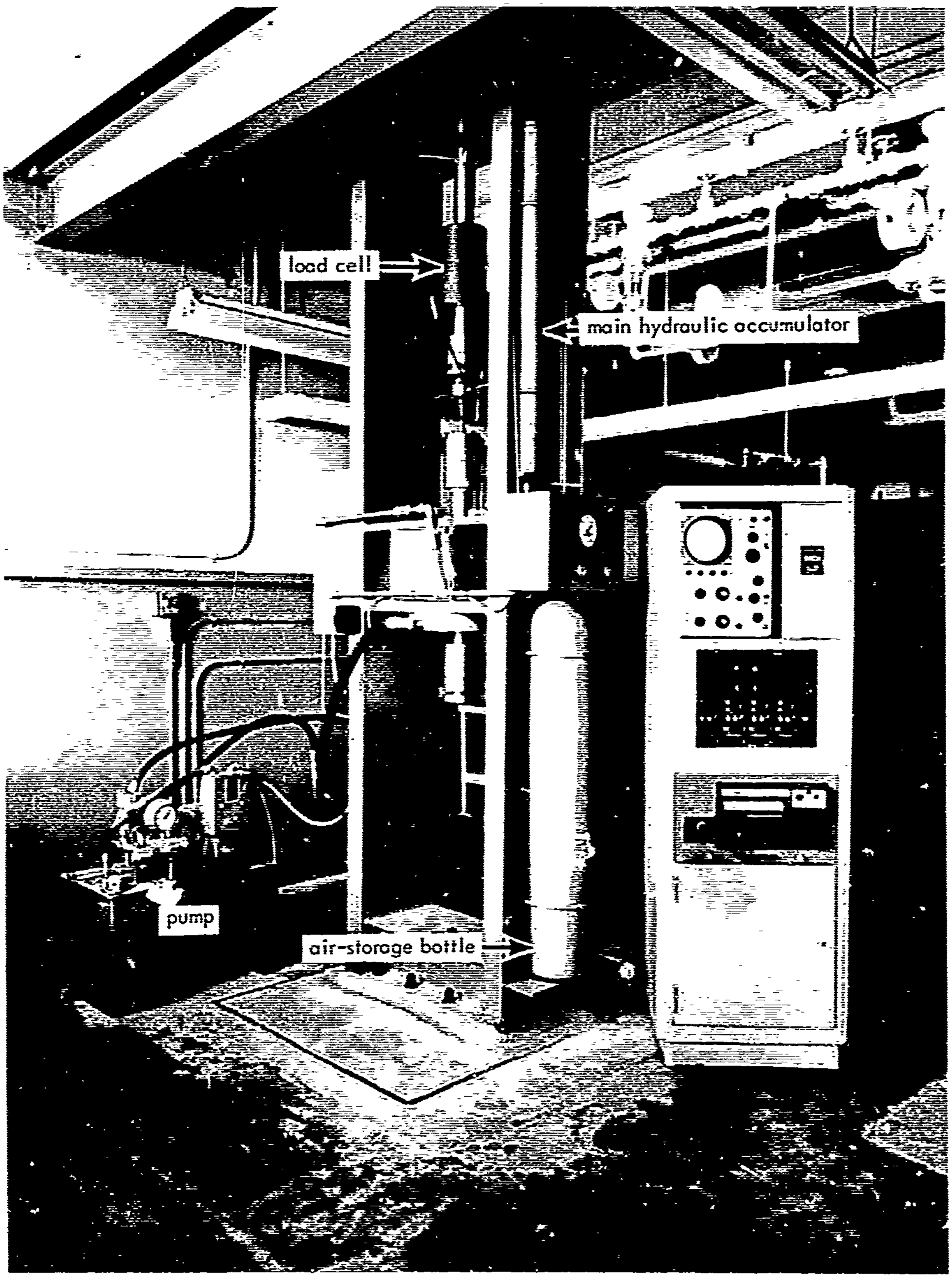

Figure 1. NCEL dynamic testing machine.

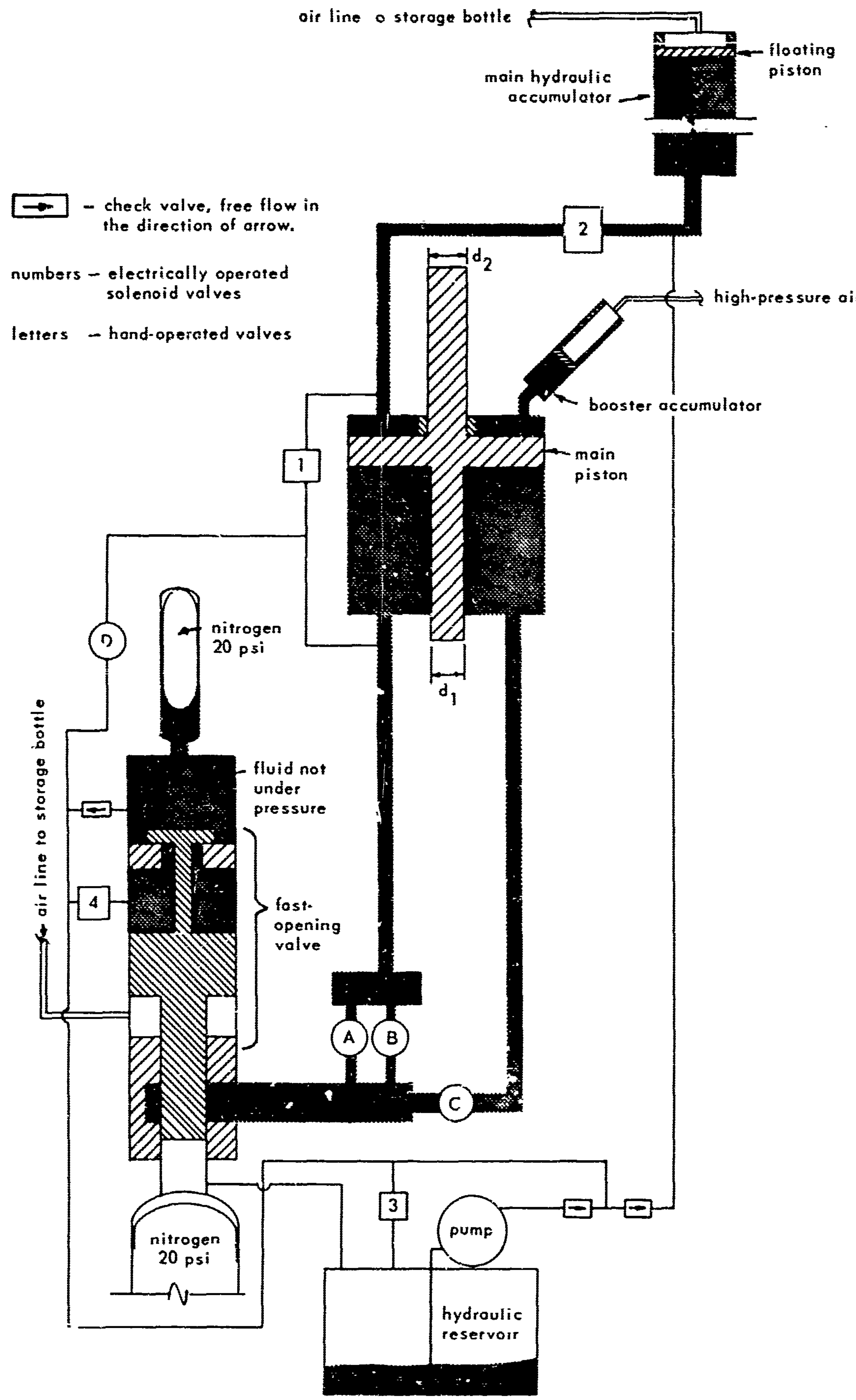

Figure 2. Schematic diagram of dynamic testing machine just prior to test.

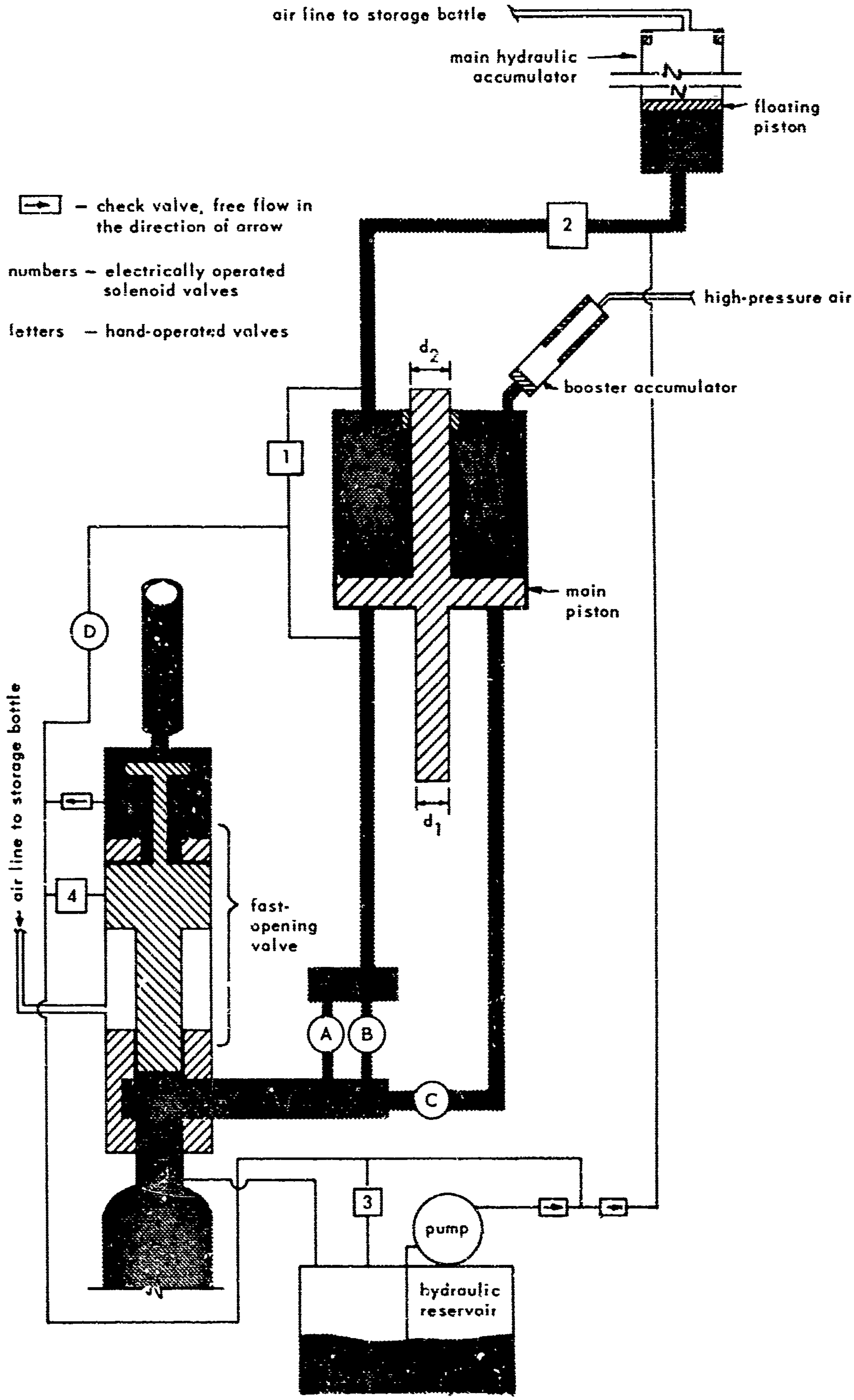

Figure 3. Schematic diagram of dynamic testing machine at the conclusion of a test.

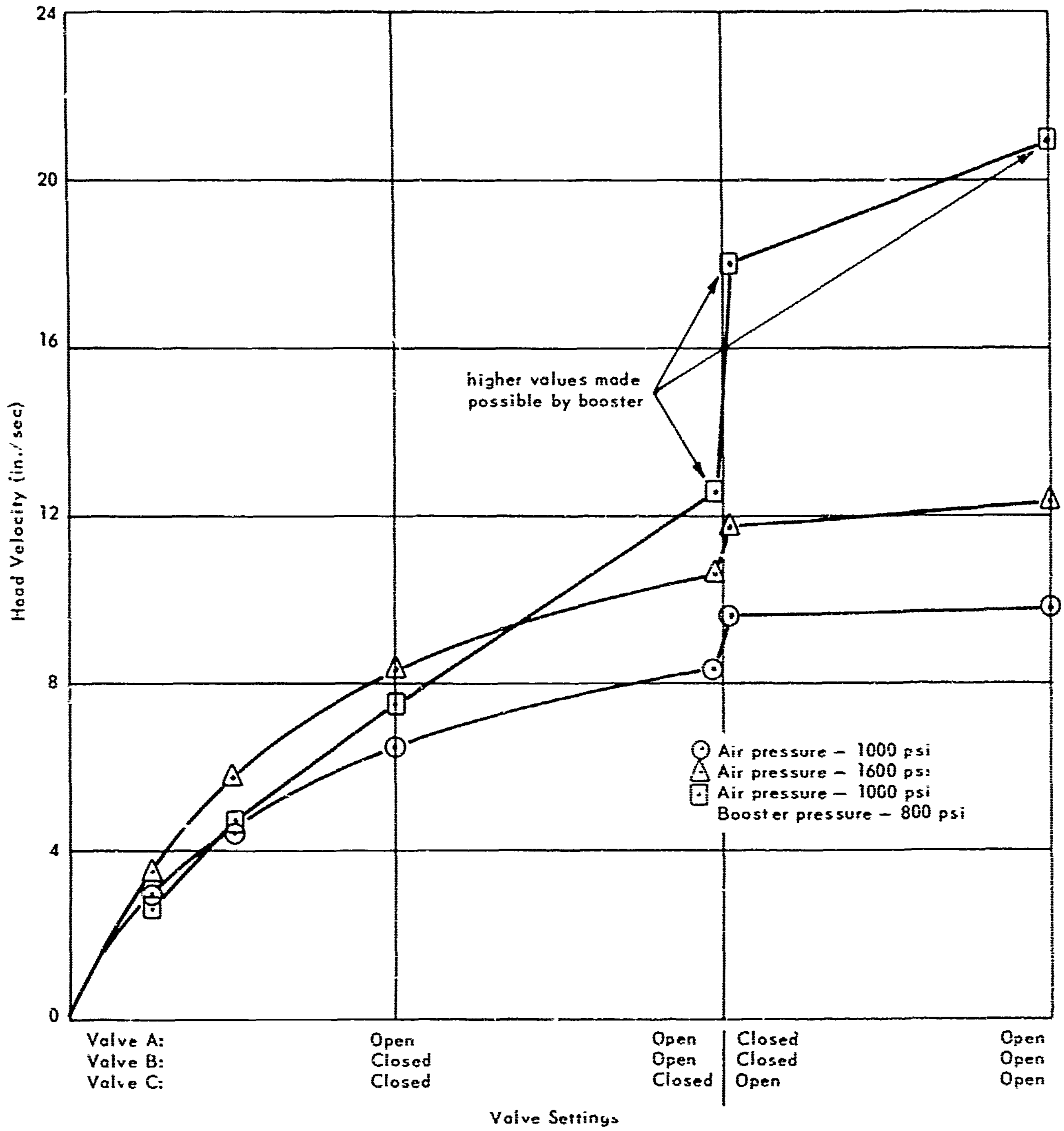

Figure 4. Head velocity vs valve settings.

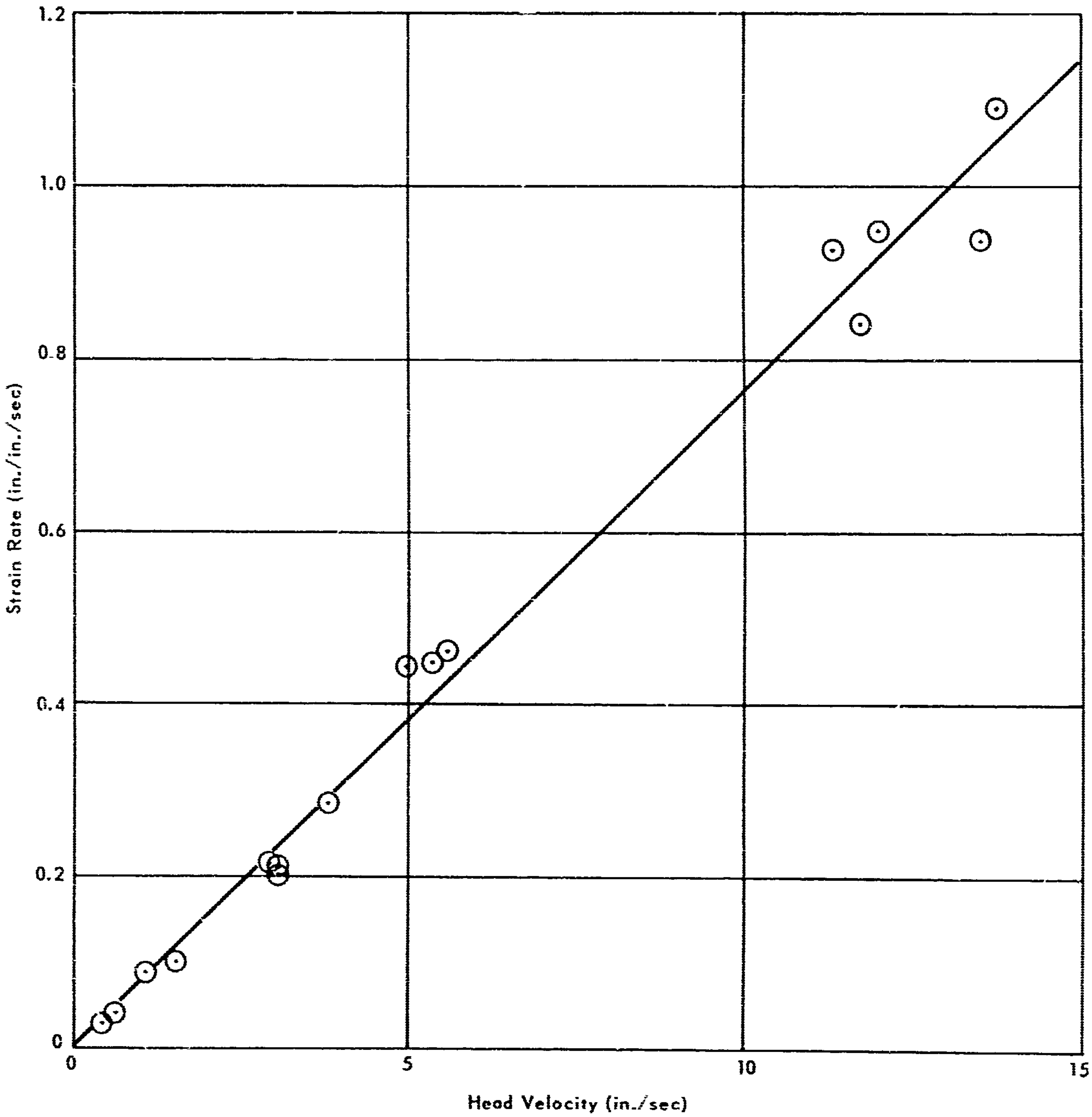

Figure 5. Strain rate vs machine head velocity.

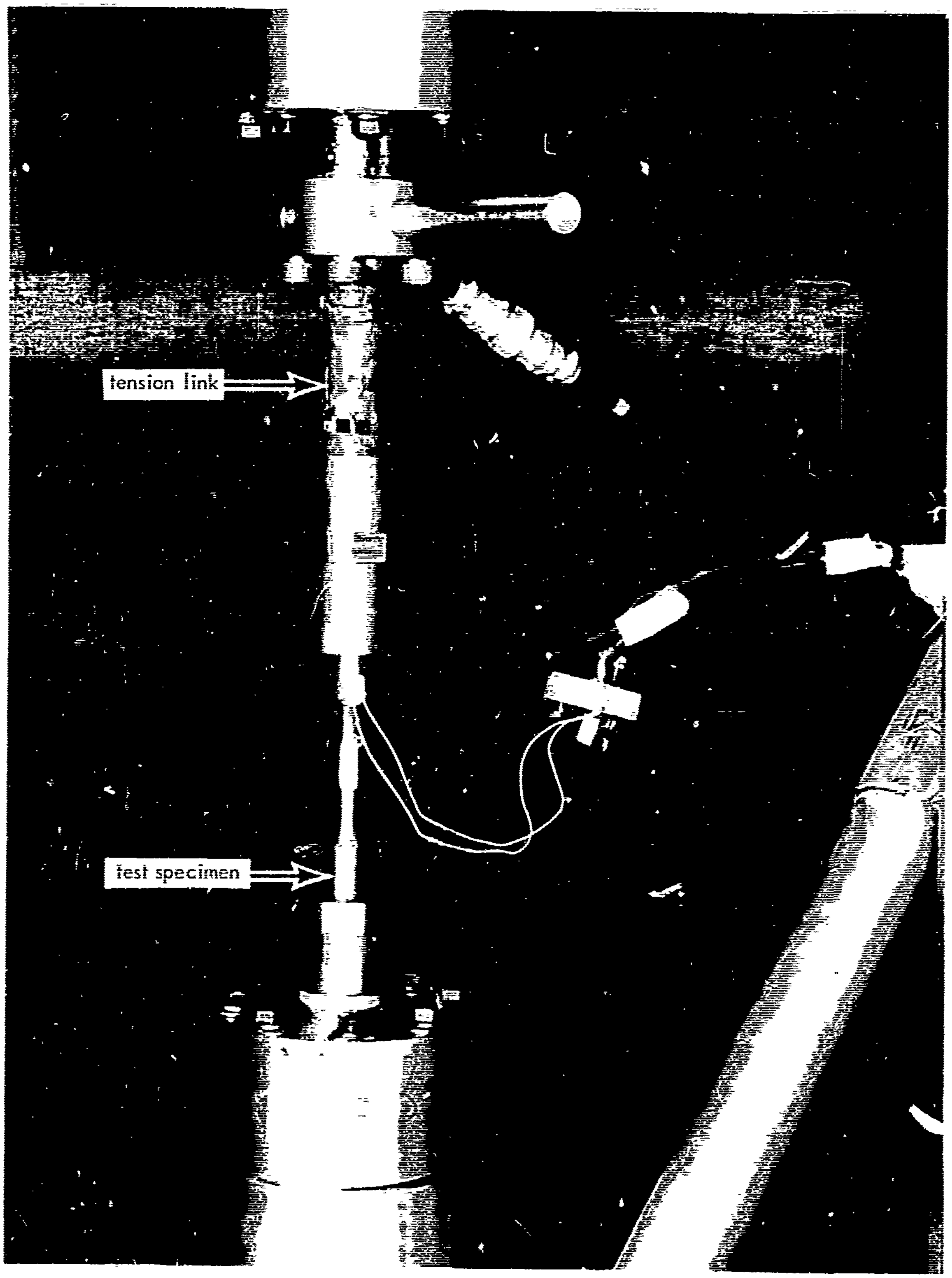

Figure 6. Typical test setup showing tension link and test specimen in place.

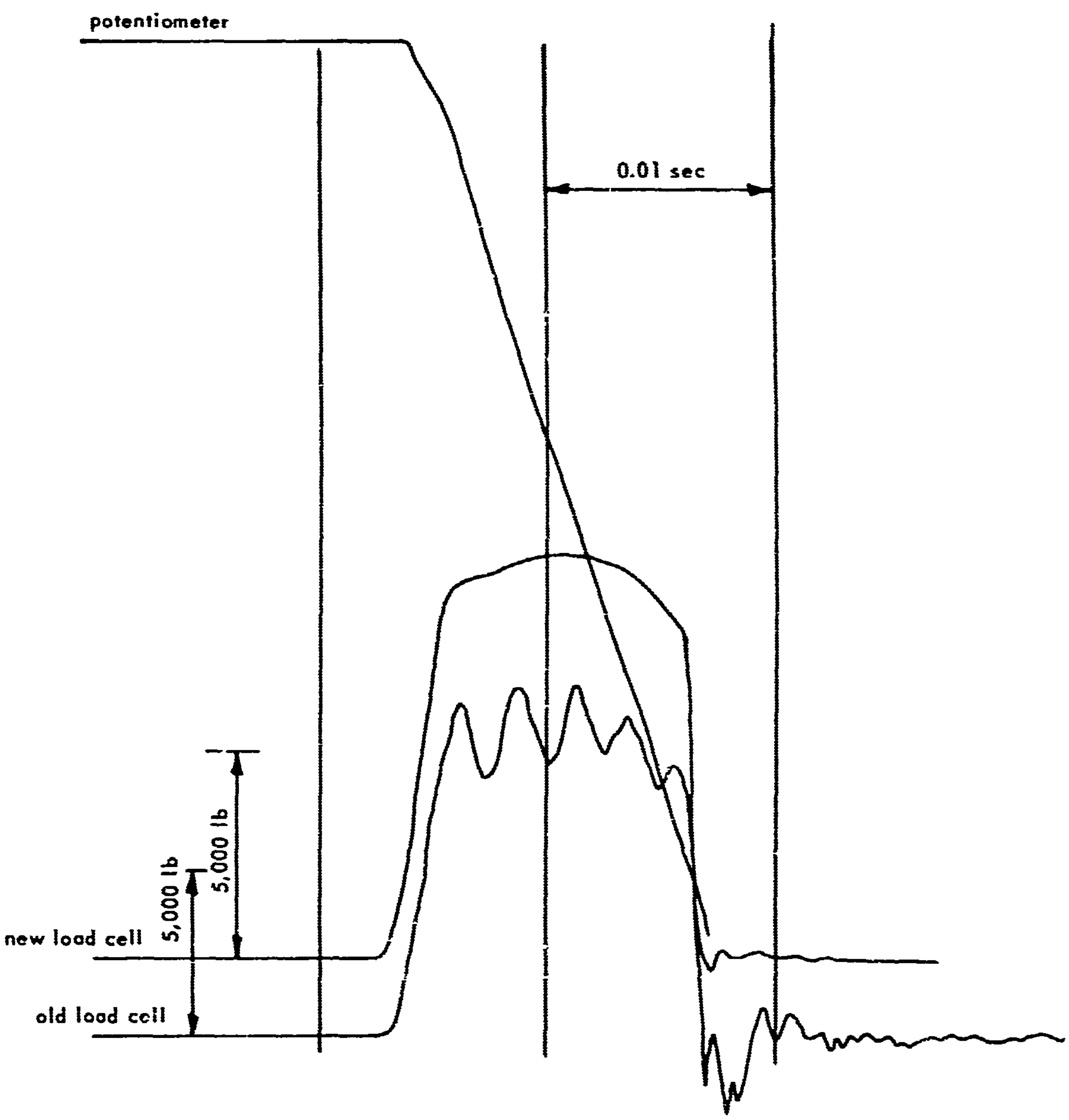

Figure 7. Oscillograph record comparing load cell characteristics.

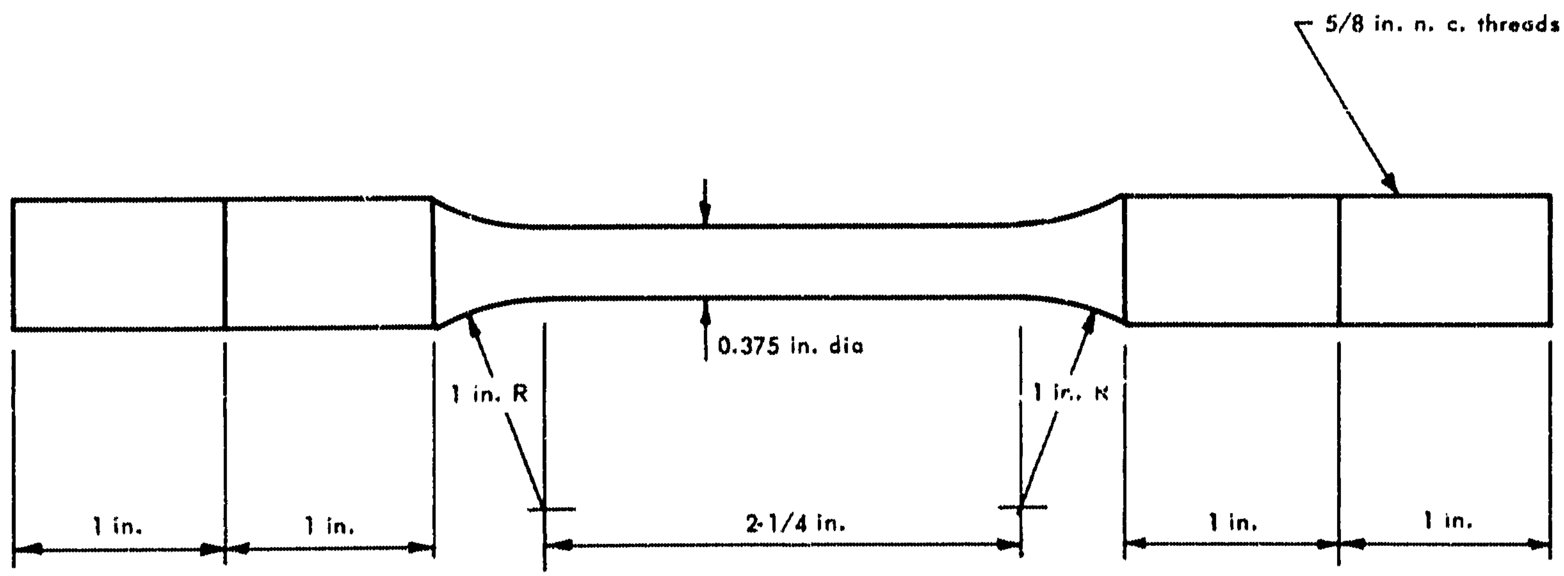

Figure 8. Test specimen.

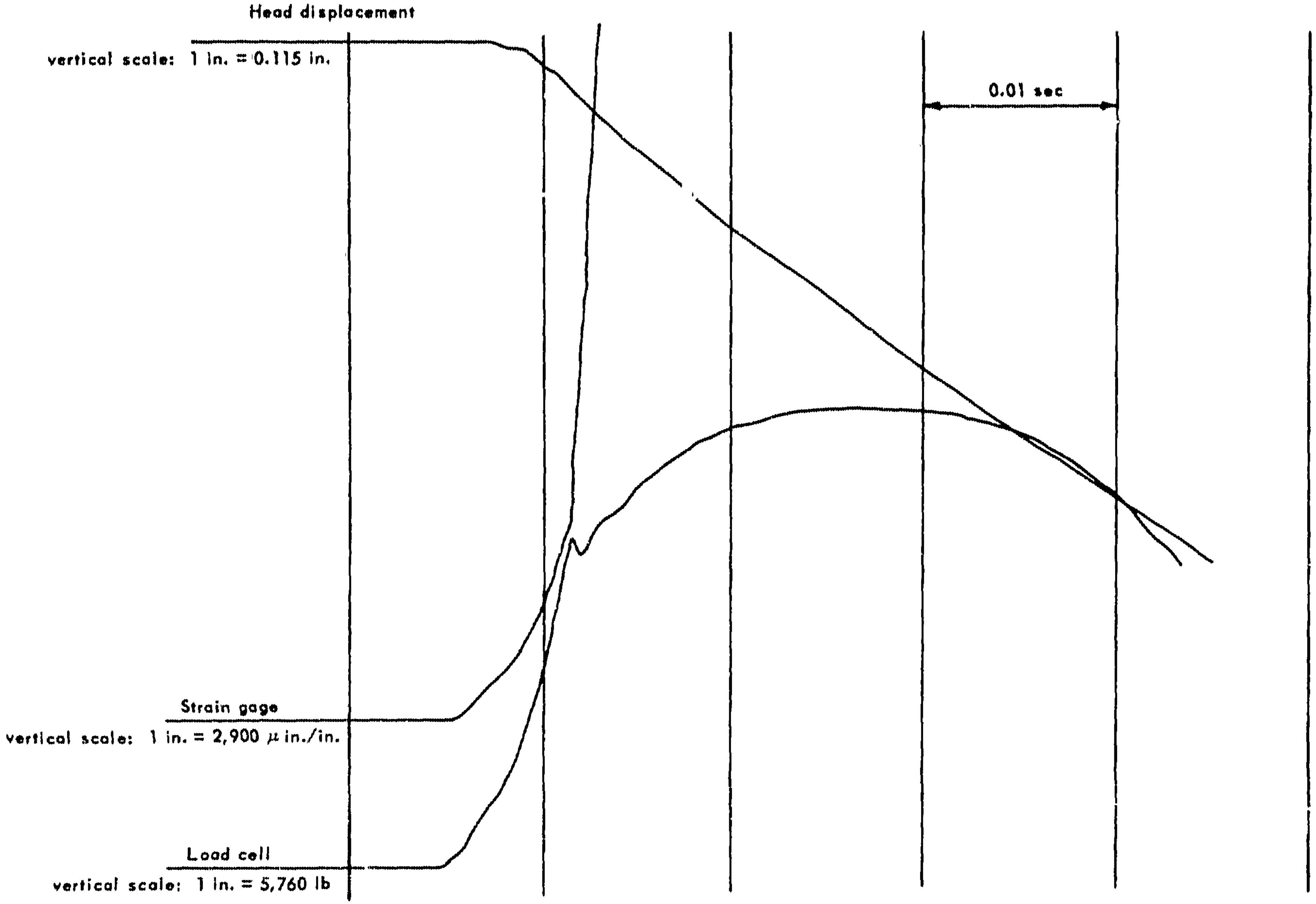

Figure 9. Typical oscillograph record of tension test on the chrome-alloy steel.

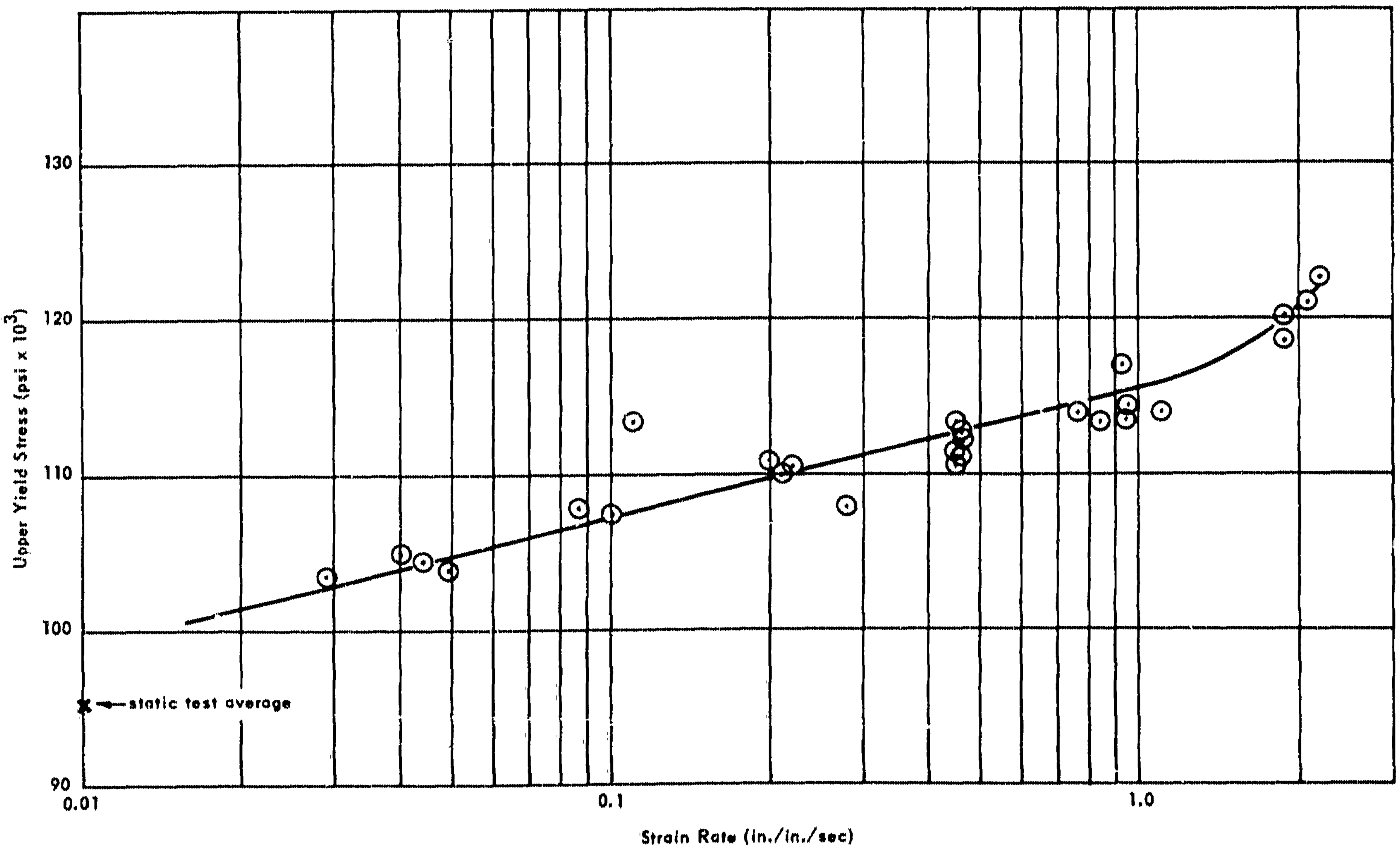

Figure 10. Strain rate vs upper yield stress.

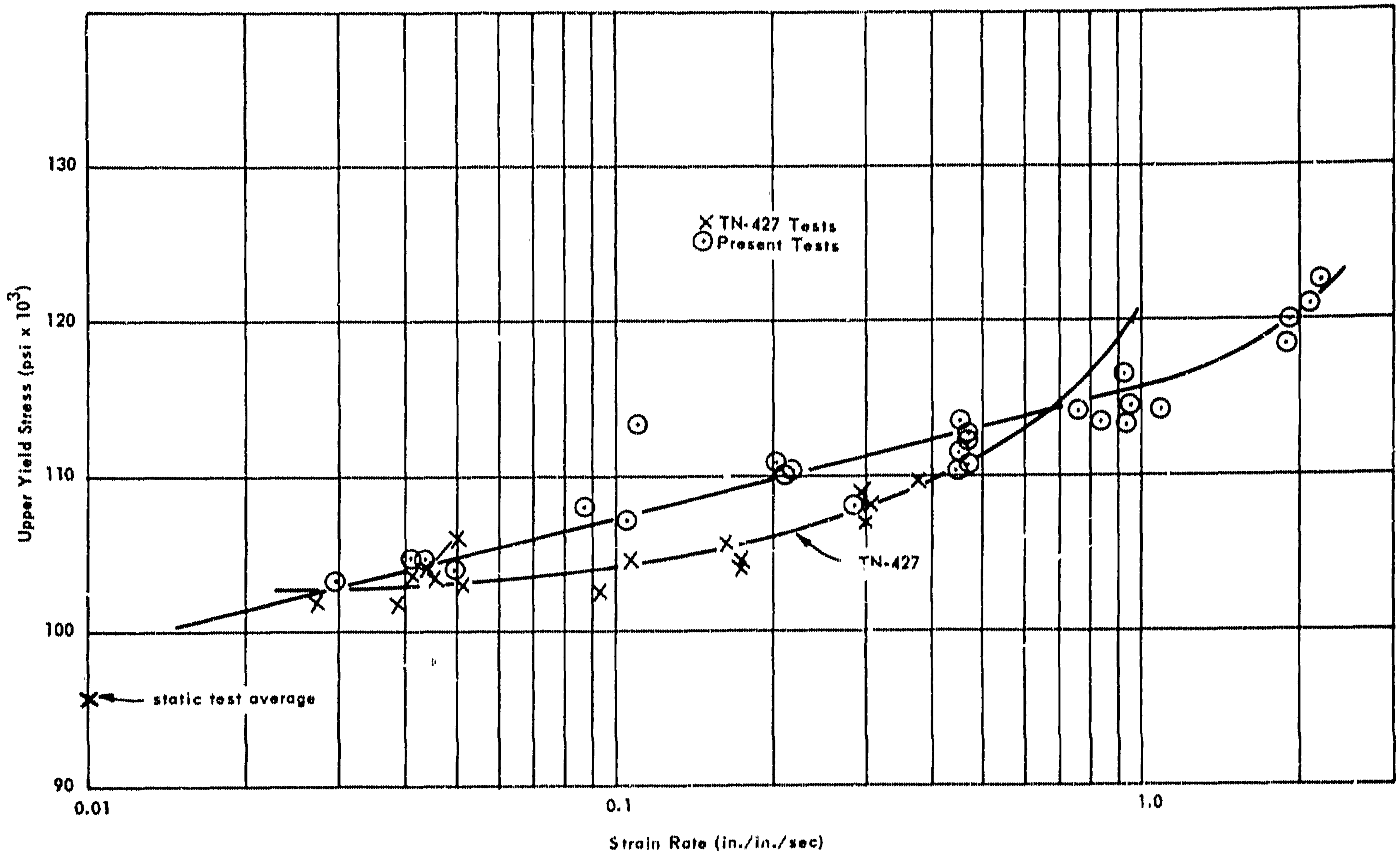

Figure 11. A comparison of present tests with the results in TN-427.

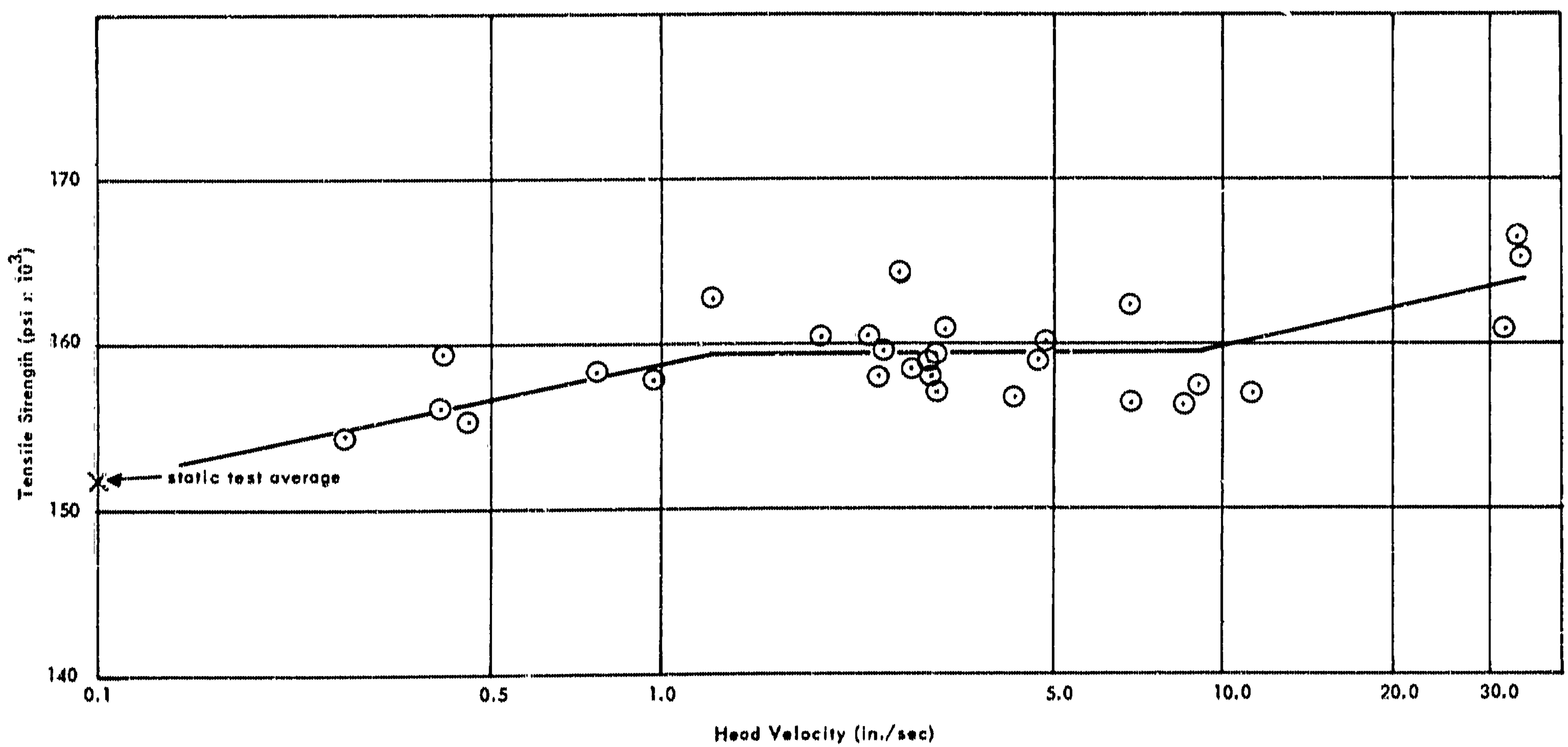

Figure 12. Machine head velocity vs tensile strength.

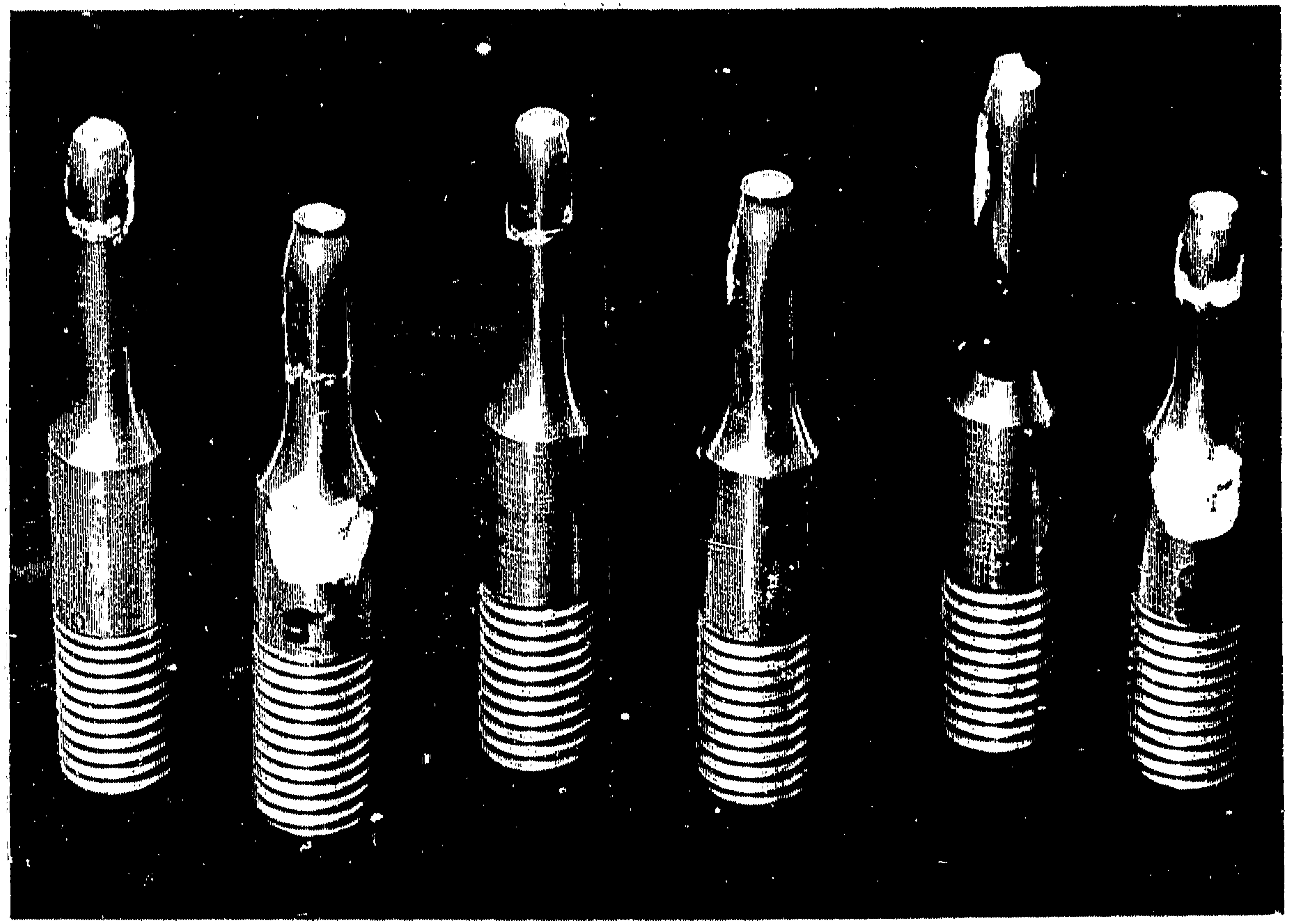

Figure 13. Tensile test specimens broken at high strain rates.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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Dynamic	0					
Dynamic Tests			8	3		
Tensile Strength			8			
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